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Formation of multiphase plasma in galactic haloes and an analogy to solar plasma

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Thermal instability (TI) potentially explains the origin of cold gas in the intracluster medium (ICM), which is heated sufficiently by AGN feedback. The Hα filaments seen in cluster cores provide strong motivation for TI. The hot (~10^7 K) ICM coronae allow the growth of isobaric TI. The multiphase medium (cold-dense—hot-diffuse) forms once TI saturates. However, gravitational stratification can spatially constrain TI, and thermal conduction is known to stabilize all scales below the field length (λ_F). In addition, the transport of energy is anisotropic along magnetic fields. Thermal conduction may further trigger gyroscale instabilities and effective reduction of λ_F. However, cold gas at small scales (<λ_F) needs to be verified in observations. The virial temperature in galactic haloes is lower (~10^6 K) and opens the regime of isochoric TI. In this regime, the cooling time is typically shorter than the sound-crossing time, and large-scale isochoric clouds are rendered unstable. The linear and non-linear isochoric clouds have interesting differences which potentially lead to either fragmentation of the cloud or not. On saturation, TI produces a turbulent medium that helps mix phases and thermalize kinetic energy and thus completes a cycle of condensation and heating. Various aspects of condensation, stratified turbulence, and magnetized transport are physically identical in solar coronae but scaled down to lower luminosity (similar temperatures). We will discuss the recent progress in TI, its connection to observations, and the analogy to solar prominences.

KEYWORDS

circumgalactic medium, intracluster medium X-rays, solar corona, thermal instability, multiphase medium

1 Introduction

Galactic gaseous haloes form in the densest regions (nodes) of the dark matter web in our Universe (Springel et al., 2006). A massive black hole typically resides at the center of the node, and a massive central galaxy forms around it (Volonteri et al., 2003). A rough boundary of this gaseous halo is between the outskirts of the central galaxy and the radial extent of the node at any given redshift. Multiphase (multi-temperature) gas is ubiquitous in such galactic haloes like an intracluster medium (ICM) or a circumgalactic medium (CGM) hosted by dark matter nodes of mass $M_{DM} \gtrsim 10^{14}$ $M_\odot$ or $\lesssim 10^{14}$ $M_\odot$, respectively. The average temperature is expected to be closer to the virial temperature (~$10^6 - 10^7$ K) of the gaseous haloes depending on M_{DM} (e.g., mean temperatures in the ICM are around ~10^7 K, while mean temperatures in the CGM are lower; see Birnboim and Dekel, 2003, for details of virial temperature across haloes). ICM/CGM is dilute and optically thin (Sutherland and Dopita, 1993). Furthermore, it is maintained as a hot medium by frequent deposition of energy from the central AGN (see Harrison et al., 2018, for a recent review) or supernovae (primarily for CGM; see Efstathiou, 2000).

One of the factors that play a pivotal role in the evolution of this environment is the cold phase (~10^4 K; "cold" is relative to the background hot phase). A range of cooler temperatures (atomic or molecular) have been observed in cluster cores across wavelengths (see Fabian et al., 2003; Salomé et al., 2006; McDonald et al., 2010; Mittal et al., 2012). Such cold phases can be formed, sustained, and/or destroyed. Thermal instability (Field, 1965) is often assumed to be a primary mechanism of formation in the cluster cores because cooling flows at large scales (Fabian, 1994) are not observed (a rough thermal equilibrium is maintained by feedback; see Fabian, 2012). The other robust source of cold gas formation in the bulk ICM is stripped gas from satellite haloes (minor mergers) that can be thermally unstable in the background ICM (Yagi et al., 2007; Jáchym et al., 2017). TI is relatively less explored in global CGMs (see Esmerian et al., 2021 and for local simulations with cosmic rays, see Butsky et al., 2020, and Huang et al., 2022). However, local (spatially) hydrodynamic simulations of unstable clouds embedded in backgrounds of varying "virial" temperatures is a mature area of computational research (e.g., Gronke and Oh, 2020), motivated by CGM observations in absorption (e.g., Péroux et al., 2018). In this mini-review, we will discuss the theoretical and computational endeavors in understanding cold gas formation in cluster cores and the fate of local cooling clouds seeded in a background hot-diffuse medium.

Although the morphology of cold gas is possibly determined by the local magnetic field direction as evident from magnetohydrodynamic (MHD) simulations (Sharma et al., 2010), there is a large uncertainty on the length scales and spatial distribution of the cooling phase. Heating mechanisms and energy transport also add to the complexity of the problem across length scales which are separated by $\gtrsim 10$–12 orders of magnitude. Such a scale separation is impossible to capture with our current computational resources. We will highlight these uncertainties and consequences in this mini-review.

There are some broad similarities between the solar corona and ICM/CGM plasmas in terms of physical mechanisms of cooling/heating. However, there are large differences in the luminosities. It is interesting to discuss basic ideas that can be borrowed from coronal physics to understand the coherent scales and the thermal state of the ICM/CGM. This may also hint at observational gaps despite the progress in multi-wavelength astronomy (e.g., X-ray/UV/optical/radio/infrared).

2 Thermal instability through laws of thermodynamics

Thermal instability, as a general physical process, is discussed extensively by Field (1965) and Balbus (1986) (earlier works include TI in cooling flows; see Nulsen, 1986). It is easy to understand the process using arguments from the second law of thermodynamics. If we take the net heat loss function $L = \zeta - H$, where ζ is the rate of cooling in a given local region and H is the rate of heating, we can balance it with the loss of entropy as follows:

$$L dt = -T dS. \tag{1}$$

Here, S and T are the entropy and temperature of the fluid in consideration, respectively, and dt is an infinitesimal time. A small change in the heat loss δL incurs a change in entropy $S_0 + \delta S$ and temperature $T_0 + \delta T$ (using "+" sign without loss of generality) such that,

$$d(\delta S)/dt = -\delta(L/T). \tag{2}$$

Eqs 1, 2 are same as Eqs 1, 2 in Balbus (1986). Clearly, $\partial(L/T)/\partial S < 0$ (Eq. 3 in Balbus (1986)) is the condition of instability in which if a small spatial patch loses entropy, net heat loss is positive and the rate of change of entropy is negative (loses entropy further). This process is a runaway process in either direction (if the patch gains a small amount of entropy, it gains entropy further). We can rewrite the condition in terms of $\partial/\partial T$ by considering $TdS = dQ$ and $dQ = C_V dT$ or $dQ = C_p dT$, where dQ is the total heat gained/lost and C_V/C_p are heat capacities at constant density/pressure, respectively. The aforementioned instability criterion extends to the following criteria under isochoric and isobaric conditions, respectively:

$$\left[\frac{\partial \ln L}{\partial \ln T}\right]_\rho < 1, \tag{3}$$

$$\left[\frac{\partial \ln L}{\partial \ln T}\right]_\rho - \left[\frac{\partial \ln L}{\partial \ln \rho}\right]_T < 1. \tag{4}$$

Note that the aforementioned conditions are the same as Eqs 3, 4 in Balbus (1986) and reduce to $\left[\frac{\partial L}{\partial T}\right]_\rho < 0$ and $\left[\frac{\partial L}{\partial T}\right]_\rho - \frac{\rho_0}{T_0}\left[\frac{\partial L}{\partial \rho}\right]_T < 0$ under exact thermal balance, respectively (Field, 1965). We will discuss in the next section the environments where any of these (or both) instabilities are expected.

TI plays a key role in environments that are radiatively cooling and heating equally in a time-averaged sense. In most cases, there is a large uncertainty about H in any local fluid volume of such astrophysical systems. TI is still expected as there are hints of heat sources that may provide adequate rates of heating to balance cooling and means to transport that heat to relevant spatial regions. For the longest time, TI was not considered relevant in convectively stable media when cooling and heating are state functions (see Balbus and Soker (1989) and Balbus (1995), for discussion on the necessity of convective instability to generate TI). However, turbulent heating is position-dependent and is the premise of renewed interest in TI (Section 4.2 in McCourt et al., 2012).

3 Cold gas formation in astrophysical environments

3.1 Thermal instability in the ICM

It is well known for decades that the ICM core (10–20% of total size) emits vigorously in X-rays (e.g., Forman and Jones, 1982). The high-energy electrons in the ionized gas emit thermal bremsstrahlung radiation (e.g., Lea et al., 1973) at the rate $\propto \rho^2 T^{\frac{1}{2}}$. With the idealized assumption that there is no fluctuation in heating (see Section 5.4 in McCourt et al., 2012), we can rewrite Eq. 4 based on the fluctuations in the cooling rate, $\zeta = \rho^2 \Lambda(T)$, where $\Lambda(T)$ represents a cooling function (in **Figure 1A**, shows the function for dilute, optically thin gas). Clearly, from Eqs 3, 4, $\partial\Lambda/\partial T$ is

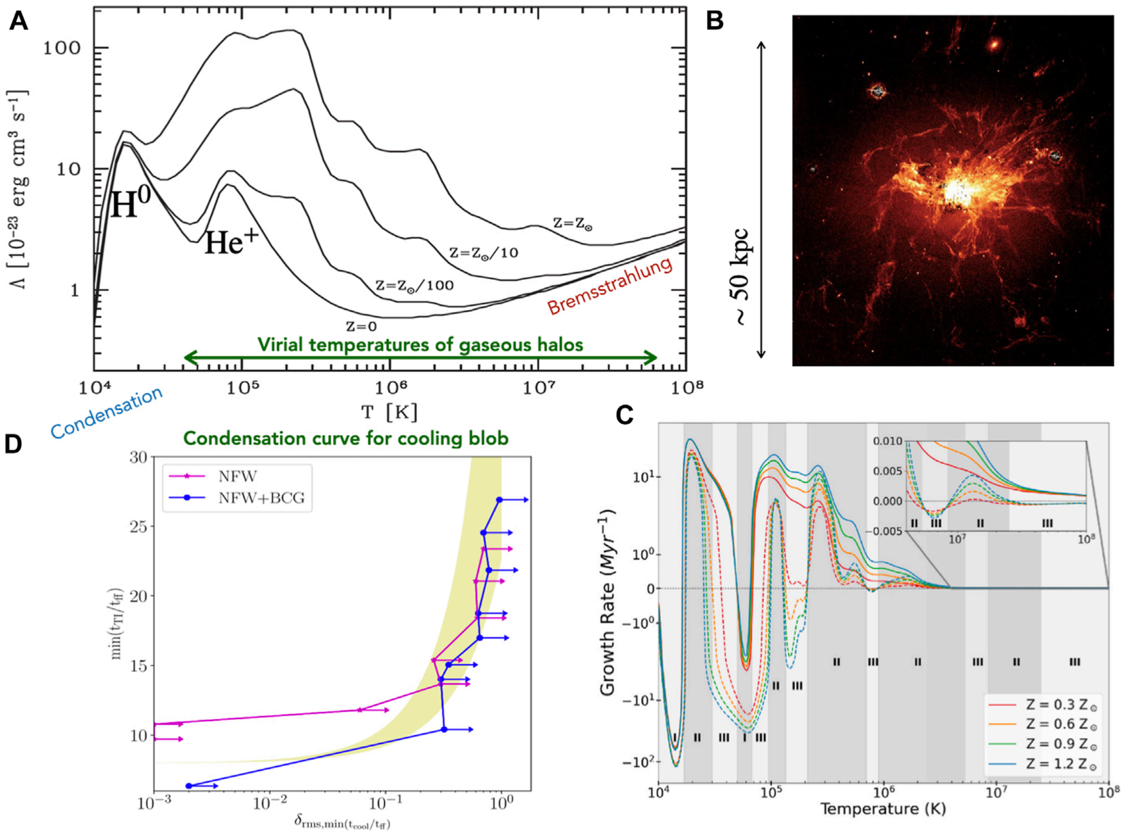

FIGURE 1
(A) Cooling function $\Lambda(T)$ as tabulated by Sutherland and Dopita (1993) for a gas in collisional equilibrium. The condensed gas is roughly around 10^4 K. **(B)** Hα emission in red in NGC 1275 in the center of Perseus cluster (Figure 1 in Fabian et al., 2008) showing the filamentary structures, and the typical dimensions are 6 kpc in length and 70 pc in width. **(C)** Cooling function showing regimes of isobaric and isochoric stability/instability. (I) denotes the regime of stability for either modes, (II) denotes the regime of instability of either modes, and (III) denotes regime of isobaric instability and isochoric stability (see Das et al., 2021). **(D)** This parametric curve shows how local thermally unstable overdensity in a background of large t_{cool}/t_{ff} (hot gas at high entropy) can lead to condensation by maintaining a local moderate ratio $t_{cool}/t_{ff} \sim 8$ (as marked by yellow using analytic estimate, Eq. 14 in Choudhury et al., 2019).

instrumental to assess the onset of TI. For cluster cores, isobaric modes are driven to runaway easily since the partial (log) derivative of ζ with respect to ρ (isothermal) is always greater than that with respect to T (isochoric) in the bremsstrahlung regime. This idea is used to explain the *in situ* formation of condensed gas which can be observed in Hα (**Figure 1B**).

Numerical explorations in hydrodynamic/MHD simulations include idealized local and global models. The idealized simulations study multiphase gas formation in stratified plane-parallel atmospheres (see, for e.g., Meece et al., 2015 and others mentioned previously), while several simulations explore the same in the global ICM-like spherical atmosphere (e.g., Sharma et al., 2012). A key assessment from such explorations is that the condensation ($\sim 10^4$ K) takes place in an overdensity if it cools relatively fast (within a few factors) compared to the free-fall rate and/or buoyancy oscillation rate (Figure 12 in Choudhury et al., 2019). Even if the hot gas in which clouds are embedded has a long cooling time ($t_{cool} \gg t_{ff}$, where t_{cool} is the radiative cooling timescale and t_{ff} is the free-fall timescale into the halo center), the condensing clouds locally maintain lower $t_{cool}/t_{ff} \lesssim 10$ (**Figure 1D**). Both conditions are intuitively clear. Fast buoyancy oscillation can saturate growth and mix the blob easily while fast infall simply enables a gas blob to accrete toward the inner galaxy. In the latter case, the fate of the blob is not certain. It may cool down to dense molecular clumps and collapse under self-gravity on its way. It may also become sufficiently dense to become optically thick and hence also be affected by coupling to radiation (see Proga et al., 2022). Optically thick gas might be better detected in absorption (unless irradiated) and hence the multiphase medium in the cluster core can be possibly revealed better by considering emission, absorption, and re-emission (e.g., Fabian et al., 2022). There is no systematic theoretical study of the formation of optically thick gas in the diffuse ICM/CGM for the lack of sufficient observational evidence. Magnetic fields may enhance condensation with a preferential morphology along the local field line (definitely when there is anisotropic thermal conduction; see **Figure 2A**, but also in ideal MHD), and the growth is known to scale with the ratio of thermal-to-magnetic pressure, also known as plasma β and β^{-1} (Ji et al., 2018; also see Fabian et al. (2008) for observational evidence).

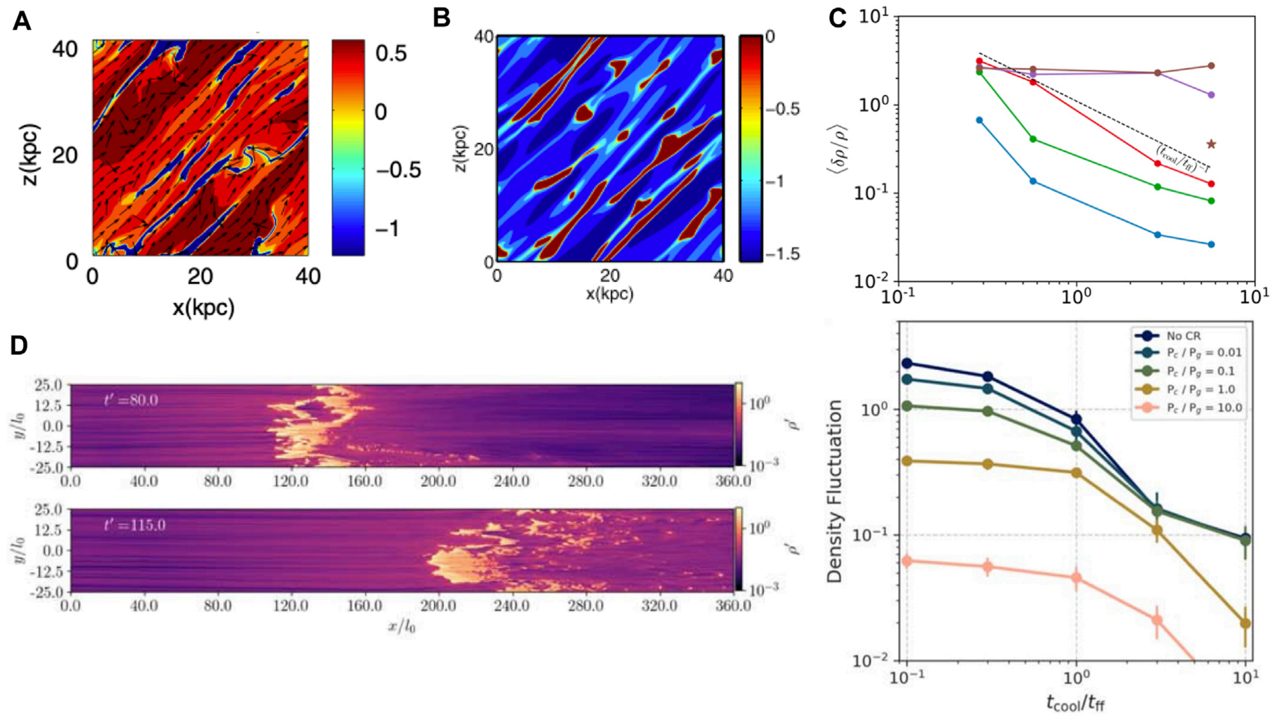

FIGURE 2
(A) Contour plots of $log_{10}(T)$ where T is the gas temperature for the non-linear stage in a MHD simulation (black arrows show magnetic field lines) with anisotropic thermal conduction (Sharma et al., 2010). The condensed gas is compressed in the cross-field direction while thermal conduction allows for the elongation along the field. **(B)** Contour plots of log_{10} (p_{cr}/p_g), the ratio of cosmic ray pressure to gas pressure, showing extension in the size of cold gas dominated by CR pressure. **(C)** The upper panel shows the scaling of growth rate of TI with plasma β and t_{cool}/t_{ff}, where blue shows the largest β and red, the smallest, and brown and purple show the cases with the galactic cooling function instead of cluster cooling function (Ji et al., 2018). The lower panel shows the same scaling with β instead of p_{cr}/p_g (Butsky et al., 2020). **(D)** Acceleration of cold clouds (here, the gas density is plotted) by CRs (Huang et al., 2022).

3.2 Thermal instability in the CGM

CGMs are not as bright as clusters due to lower virial temperature and number density. There are rare observations in the X-rays (e.g., Mathur et al., 2021), and mostly the gas is seen as absorption in the quasar line of sights (e.g., Tumlinson et al., 2013). From such studies, there is a hint that gaseous haloes or CGMs have a wider spatial extent of the cool–warm phase (Werk et al., 2016). Either this is a cooling flow (due to the rapid cooling rate at lower virial temperatures; see, for e.g., Stern et al., 2019) or due to lack of buoyancy oscillations that can saturate the formation of a cooler phase (in Figure 9, blue symbols denote the extent of cold gas without buoyancy oscillations, in Choudhury et al. (2019)). Pure TI simulations in the stratified medium with strong magnetic fields show uninhibited condensation even if t_{cool}/t_{ff} is large (purple and brown lines in Figure 8 in Ji et al., 2018) since magnetic pressure possibly fully supports unstable blobs. Cosmic ray (CR) pressure can also support and expand the cooling blobs (**Figure 2B**). However, CR may reduce the growth of cold gas if the transport is efficient (see Butsky et al., 2020 and **Figure 2C**).

More recently, local cloud simulations embedded in a wide range of diffuse environments and virial temperatures have been explored. In the simplest case, the linear and early non-linear evolution of a cloud depends on isobaric or isochoric stability conditions described in Eqs **3**, **4** (Waters and Proga, 2019; Das et al., 2021; see **Figure 1C** for the two regimes across a range of temperatures and cooling rates). If both isochoric and isobaric instability criteria satisfy, the cloud collapses into a single monolithic dense clump, but if the isobaric criterion holds, only then does a large-scale cloud break into small-scale growing clumps ("shattering"). The late non-linear evolution of cold clouds (also known as the "cloud-crushing problem" when there is a background velocity gradient; see Kanjilal et al., 2021) further depends on the sizes, density contrasts, and environmental impact like a supply of gas in a static background medium (e.g., cooling flows around individual clouds, Dutta et al., 2022), dynamic state of the background in case of outflows (Farber and Gronke, 2022), CR-driven outflows leading to efficient acceleration (Part **D** in **Figure 2D**), etc (see Faucher-Giguere and Oh, 2023 for a recent review on CGM).

The smallest scale of cloudlets is known to be set by the scale at which thermal conduction can suppress TI; this is called the field length (λ_F). λ_F is often orders of magnitude smaller than global ICM/CGM gradient scales. More recently, the length crossed by sound in a characteristic cooling time ($l \sim c_s t_{cool}$, where c_s is sound speed) is also discussed as the characteristic clump scale (McCourt et al., 2018). However smaller cloudlets are also seen in simulations (see Section 6.3 in Das et al., 2021). In realistic scenarios, clouds of size l may collapse under self-gravity if t_{cool} is comparable to the timescale of collapse onto itself (Jeans' criterion). The smallest scales of cold gas, the connection to TI, and how these may appear in observations have been pursued in large-scale cosmological simulations (e.g., Nelson et al., 2020) including limited physical processes.

3.3 Analogy to solar prominences

Solar prominences have commonalities with the condensing gas in the ICM. These are also dense, stretched gases at a relatively lower temperature than the background environment (see Parenti (2014), for a review of observations and Gibson (2018), for a review of models). These are observed as bright structures in the chromosphere (see **Figure 1** in Parenti, 2014) and seen in absorption in the corona (outside the chromosphere). The absorption prominence is possibly optically thick. However, there is extensive information on the magnetic field around such structures. Typically, the prominences are seen above the polarity inversion line (PIL) in the solar corona (e.g., Okamoto et al., 2008). The morphology of the condensed region is known to also closely follow the PIL and local magnetic field lines, and in fact, the length can be of the solar diameter scale. While the temperature and density contrasts of prominences relative to their backgrounds are similar to ICM condensation, the details of the magnetic field configuration are unknown in the ICM/CGM. Hence, the solar magnetic fields may hint at the configuration of ICM/CGM fields too (although average β is much smaller in the Sun). The dynamical stability of prominences is discussed in the literature based on mass flows inside the prominence or the magnetic fields. The former idea can be similar to how we assess the cloud evolution ("shattering" or not) in the CGM. There is extensive discussion on the prominence dimension, and a wide spectrum of dimensions is favored by observations. Such ideas are aligned with the absence of a characteristic scale for cold gas in diffuse media.

The origin of solar prominences is explained by several models (e.g., thermal imbalance in Antiochos and Klimchuk (1991), reconnection in Kaneko and Yokoyama (2017), and supergranulation in Liu and Xia (2022)). However, there are interesting parallels with the debate over the precise location of prominence formation and the origin of cold gas in the galactic haloes. It is uncertain if solar prominence is formed *in situ* in the chromosphere, levitates from the chromosphere to the corona, or separately condenses within the corona. Similarly, the origin of cold gas in galactic outflows is an ongoing debate between *in situ* formation and lifting by the outflows.

3.4 Connection between heat source, heat transport, heating mechanisms, and cold gas formation across scales

The exploration of what amount of heat is available at various spatial locations in a given astrophysical environment made of plasmas (ICM/CGM/Sun) is the key missing piece in constraining cold gas formation models. It constrains not only energy transport physics but also the scales of cold phases. Observationally, this is useful to assess what is unseen and what sort of multi-wavelength explorations are necessary for the future. The energy transport problem has been pursued for decades. It spans across collisional (Coulomb) and collisionless domains. Our current tools allow us to extensively study these two regimes separately in MHD simulations and particle-in-cell (PIC) simulations. Consequently, we understand issues in either regime well. However, real ICM plasma transits dynamically across the collisional and collisionless regimes. The cross talk across such an enormous range of length scales can become substantially significant in the global energy transport processes, which in turn impacts how much energy is available far away from a heat source. We will discuss our current knowledge about heat sources in the following sections.

3.4.1 What do we know about heating in the ICM/CGM?

Large-scale cosmological simulations and global idealized simulations use sub-grid models associated with the heating and feedback cycles in clusters or gaseous haloes, motivated by persistent observational evidence (e.g., Kay et al., 2002; Sijacki et al., 2007; Oppenheimer and Davé, 2008; Nelson et al., 2015; Masterson et al., 2023). These models are based on the idea that sub-halo scale (at scales larger than the central galaxy) mass accretion leads to a sustained supply of cooling phase near the central galaxy and a fraction of this phase eventually feeds the central black hole. The feeding promotes fast outflows as jets (seen in radio in the clusters) which deposit the kinetic energy into the ICM/CGM to heat it (e.g., Prasad et al., 2015; Li et al., 2015; Yang and Reynolds, 2016; see Donahue and Voit, 2022 for a recent review). In the CGM, another form of feedback happens *via* supernova explosions, triggered by star clusters in the interstellar medium (this feedback is not dominant in clusters). The microphysical evolution of accreted material from the sub-halo scale to the black hole magnetosphere, to produce outflows, is unclear and debatable (see Talbot et al., 2021 for a recent exploration). The net effect of the process is captured well in phenomenological sub-grid models with an assumed efficiency of conversion of accreted energy to outflows. Despite missing details, the central engine as a heat source is well justified and corroborated by observations (Cresci and Maiolino, 2018). However, how this kinetic energy is transported across sufficiently large distances and converted to the thermal form is not well constrained. In the hydrodynamic regime, compressible waves (e.g., Bambic and Reynolds, 2019) and incompressible isobaric turbulence (e.g., Mohapatra et al., 2020) have been discussed as energy carriers and mediators of dissipation (e.g., Choudhury and Reynolds, 2022). The central AGN activity is taken to be the generator of both the carriers, but stratification limits the spatial propagation of incompressible waves/energy carriers (e.g., Reynolds et al., 2015; also seen in Choudhury and Reynolds, 2022). Coupling between cosmic rays and magnetized ICM is also found to be mediating energy transport and dissipation (e.g., Zweibel, 2017).

3.4.1.1 Connection to the smallest physical scales: Plasma physics

The central problem is the conversion from bulk kinetic energy to thermal energy. If turbulence is present, the cascade provides an efficient way to reach local viscous scales. On the other hand, thermal conduction is the direct mode of transporting thermal energy to a large distance along a temperature gradient. However, the magnetic fields in the ICM are known to be within a few μG. This leads to very small electron gyroradii ($r_g \sim$ npc) compared to the Coulomb mean free path ($\lambda_{\rm mfp} \sim$ kpc). Hence, the heat transport *via* electrons is locally anisotropic and less efficient in the cross-field direction (Braginskii, 1965). Thus, the heat flux is typically lower than the expected isotropic flux. Furthermore, depending on how large or small the temperature gradient scale is relative to $\lambda_{\rm mfp}$, the plasma is collisional or collisionless. In the absence of collisionality, the electron thermal flux can saturate at even lower values ($\propto \beta^{-1}$) due to the scattering of electrons by unstable electromagnetic waves at the electron gyroscale (e.g., Roberg-Clark et al., 2016). The transport problem is generic to any plasma and hence important even in the CGM. Such suppression of conduction simultaneously enables compressible waves to travel without decaying across large distances and opens up small-scale growth of TI (Section 5 in Drake et al., 2021). It will be interesting to pursue the implications of such microphysical processes for the global cold phase and feedback.

3.4.2 Analogy to the heating problem in solar coronae

The coronal heating mechanism is an unsolved issue for decades (De Moortel and Browning, 2015). The problem is about the maintenance of the tenuous corona visible in extreme X-ray and ultraviolet, outside the star. It requires the identification of a source to balance the loss of energy due to radiation, convection, and thermal conduction. This is identical to the sustenance of diffuse ICM except for the latter where we know that a powerful central engine can deposit energy intermittently. However, transport processes vary with plasma β (e.g., Roberg-Clark et al., 2018); hence, suppression of heat flux may not be prominent in the solar corona.

Among the various modes of transport discussed for the energy to reach the corona (see Parnell and De Moortel, 2012), two of the primary ones are acoustic and MHD waves (e.g., Zweibel, 1980). Convection of energy may happen from the lower layers of the Sun. This will generate compressible and incompressible waves. The efficiency of transport of fast waves like Alfvén or magnetosonic is debatable. Adequate energy flux should be transported to the right location and converted to the thermal form, and damping of waves may not necessarily imply dissipation. Since magnetic fields are stronger, these are considered dynamically important and another primary contender which mediates heating. Heating due to interchange of magnetic reconnection in the vicinity of open magnetic field lines (Bale et al., 2022) or ohmic heating induced by nanoflares (in small-scale current sheets associated with bipolar field regions; Parker, 1988) is strongly favored currently. Despite a subdominant average magnetic field in the galactic haloes, some of these magnetic processes can be interesting to explain the local energetics near condensed gas where a strong magnetic field can develop. In fact, in the context of AGN uplifted cold filamentary gas and dragged magnetic fields, magnetic reconnection has already been evoked to explain how emission lines (e.g., Hα) are powered in the dense, cold filaments (Churazov et al., 2013).

3.5 Computational challenge

Computationally, the astrophysical systems discussed in this mini-review are modeled using massively parallel codes evolving the hydrodynamics (in the case of the fluid regime) or the particle trajectories and electromagnetic fields (in the case of the collisionless plasma regime). The two regimes are scale-separated. The media can transit between the two regimes dynamically. The biggest computational challenge in understanding cold, dense gas and hot, diffuse gas is the insurmountable gap between interesting length scales and timescales. With current resources, we cannot resolve the largest and smallest relevant scales simultaneously. Consequently, the cross talk across scales is not understood. The current efficient way to study condensation and energy transport is to choose interesting ranges of scales. However, the computational frontier is rapidly making progress to bridge this gap using upgraded hardware/software in the models of astrophysical environments.

4 Concluding remarks

In this mini-review, we discussed condensing gas in the ICM/CGM and the similarities and differences with solar prominences. We explore if there are parallels between the origin and destruction processes. The magnetic fields are better understood in the solar corona due to shorter timescales of the evolution. Some insights learned from solar prominence and corona can be scaled up and applied to the ICM/CGM. However, there is missing information in both kinds of atmospheres in computational models. For example, how dense and optically thick the condensed gas is, or in other words, if we expect to see this gas in absorption or emission, is not clear. Furthermore, at the interface of dense and diffuse gas, the state of collisionality changes. A breakthrough may take place if weak collisionality can be modeled well in the particle-in-cell simulations since that evolves a system from the first principles. Another Frontier to understand cold, dense gas both in solar/galactic corona will be to predict the impact of coupling between dense, cold gas and radiation. To summarize, both fields of research have interesting takeaways from each other.

Author contributions

PC drafted and revised this manuscript.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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